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A Radiative Transfer Model for Acoustic Propagation in Ocean Sediment Layers

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LONG-TERM GOALS

The propagation of mid-frequency (1-10 kHz) acoustic waves in shallow water regions (depths of 100-200 m) is strongly influenced by the characteristics of the ocean bottom. While there has been much progress in developing and validating bottom scattering models, much of the focus has been in the high frequency regime with comparatively less focus in the mid-frequency. This is an important topic, since in the mid-frequency regime the acoustic field can penetrate the rough interface into the sediment and undergo multiple scattering from sediment stratification and volume inhomogeneities. In this work, the long-term goal is to develop an understanding of the spatial and temporal characteristics of the acoustic field through a rigorous modeling and measurement effort. In addition, the feasibility of using tools such as chirp sonar for bottom characterization will be considered and assessed.

OBJECTIVES

The objective of this research is to examine the acoustic scattering physics in the mid-frequency regime to isolate and characterize the scattering contributions due to bottom roughness, sediment stratification, and embedded volume scatterers. A further objective is to evaluate the use of a chirp sonar system for characterization of the ocean bottom. This will provide a means for accurately quantifying parameters such as reflection losses and bottom penetration over a broad frequency range in support of Navy sonar applications.

APPROACH

The technical approach for this work is as follows:

1) Identification of a mathematical model for ocean bottom scattering: The Radiative Transfer (RT) formulation was identified as a promising framework to study random media scattering, due to its ability to handle combined layer and volume scattering[1-3]. The RT formulation has been successfully applied in electromagnetics remote sensing, in geometries similar to the ocean bottom sublayers (i.e. discrete scatterers within parallel-plane layers). It has also been suggested

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in the acoustics community[4] for seismics[5] and material analysis[6], but had not yet been applied to ocean acoustics.

2) Comparison of the RT model with a classic scattering model: since the RT equation can be derived from fundamental principles of wave propagation, its results can be compared to classic models. The RT model for ocean bottom scattering will be compar[ed] to the integral equation method using weak scatterers (Born approximation). The RT formulation has the advantage that it is not restricted to the assumption of small perturbations.

3) Implementation of the Transient RT formulation: Most of the researc[h] on Radiative Transfer has been done for steady state conditions (i.e. the media is excited by a permanent source at a single frequency), but most of the experiments on scattering are conducted by exciting the media with broadband finite pulses[6,8]. The Transient RT formulation will allow handling this kind of excitations.

4) Tank experiments to validate the model: Scaled tank experiments were conducted at ultrasound frequencies using well characterized random media such as a substrate slab with embedded glass beads and aluminum scatterers distributed in fine sand. The measured scattering cross section was compared to the scattering levels predicted from the RT simulator.

In tandem with the development of a new ocean bottom RT, analysis of data from the Shallow Water 2006 experiment (SW06) was ongoing. The SW06 data shows that volume scattering is mostly due to subbottom layers and depth-dependent sound speed gradients in the top sediment layer. For this reason, further developments of the RT model must be adapted to include the effect of gradients (as opposed to discrete scatterers).

WORK COMPLETED

- The approach for Ultrasound Radiative Transfer presented by Turner and Weaver [4] has been adapted to Ocean Acoustics, for a three-layer model that consists on a water column on top, a finite layer of sediment with discrete spherical scatterers in the middle and an infinite half space at the bottom. The implemented RT model assumes flat boundaries between layers and uses elastic plane wave reflection and transmission coefficients to model the coupling of energy. The solution given by this model corresponds to steady-state excitations. The RT formulation for ocean bottom scattering and demonstration of the conservation of power in lossless media are explained in detail in Quijano et al[9-11].

- Implementation of the Transient RT equation: The Transient RT formulation is based on several publications[6,8] , and it will be used to model volume scattering from the sediment as a result of applying a broadband finite length pulse of energy[12]. This resembles more closely the experimental conditions of tank experiments and field experiments (like SW06) for comparison and validation of the RT model.

- Tank experiments were conducted at the NEAR-Lab measurement facility using several combinations of background materials and scatterers, in the frequency band 200 kHz-500 kHz. The experiments allowed testing the proposed RT model by varying experimental parameters

such as the frequency range, attenuation of the background media, concentration of scatterers and its size relative to the wavelength of the excitation signal. Experimental data from published results was also favorably compared to the RT model.

- A future extension of the current model is the incorporation of rough interfaces via Kirchhoff scattering.

DESCRIPTION OF THE RT MODEL

Details of the theory and implementation of the RT equation for steady state excitations is explained in a published paper[10]. In summary, the RT equation gives a solution to the general problem depicted in figure 1, where the incident longitudinal wave in the water column can excite multiple streams of longitudinal($S_1^{L1\downarrow}$) and shear (not shown) energy in the sediment containing random scatterers.

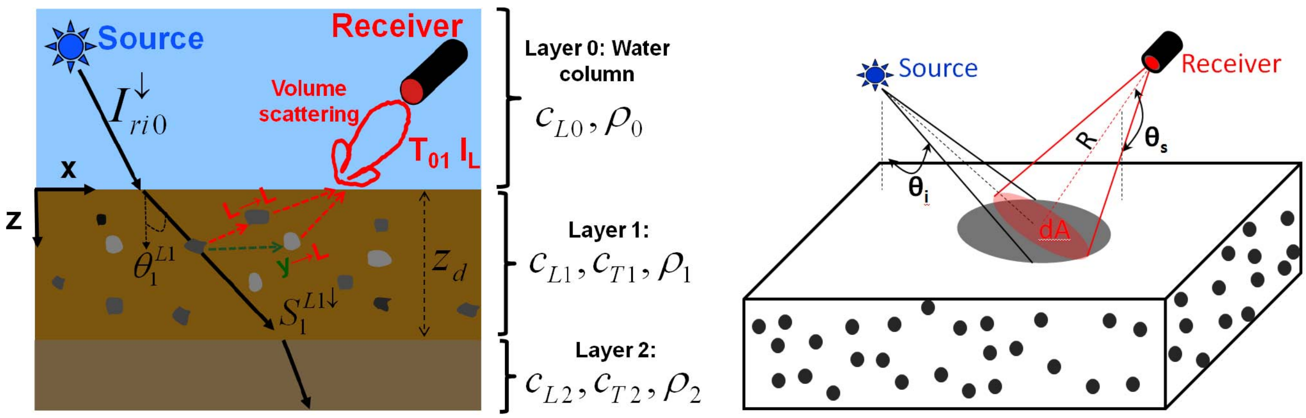

Figure N.1: (a) The incident intensity in the water column $I_{ri0}^{\downarrow}$ interacts with the water-sediment interface, giving rise to a coherent stream of intensity $S_1^{L1\downarrow}$ transmitted into layer 1. This intensity becomes a "source" of diffuse intensity in the RT equation, and is used to compute the total amount of volume scattering $T_{01}I_L$, where $T_{01}$is the transmission coefficient at the sediment-water interface. Each elastic layer is characterized by the mass density ρ_n, and the longitudinal and shear sound speeds, c_{Ln} and c_{Tn}. (b) From the RT model, the received power is found as $P_r=\int_{\Delta\Omega}T_{01}I_L d\Omega$, where $\Delta\Omega$ is the solid angle that subtends the area dA.

The RT equation that describes figure 1 is[4,10]:

$$\cos\theta \frac{\partial I_L(\theta,\emptyset,z,t)}{\partial z} + \frac{1}{c_L}\frac{\partial I_L(\theta,\emptyset,z,t)}{\partial t} = -\eta\sigma_L I_L(\theta,\emptyset,z,t)$$

$$+\frac{\eta}{4\pi}\int_0^{2\pi}\int_0^{\pi}\left[P_{LL}I_L + P_{xL}I_x + P_{yL}I_y\right]\sin\theta' d\theta' d\emptyset' + S_{1L}^{\downarrow} e^{-\frac{\eta\sigma_L z}{\cos\theta_1^{L1}}}\delta\left(t-\frac{z}{\cos\theta_1^{L1} c_L}\right) \qquad (1)$$

where I_L is the longitudinal diffuse specific intensity, η is the number of scatterers per volume in the random media, t is the time, σ_L is the scattering cross section of a single scatterer due to an incident longitudinalwave, P_{LL}, P_{xL} and P_{yL} are the cross polarizations from longitudinal, shear horizontal and shear vertical energy into longitudinal energy, respectively. The term $S_1^{L1\downarrow}$ represents the coherent (longitudinal) energy that propagates into the sediment, and similar terms can be added to account for multiple bounces of this coherent intensity between the boundaries of the layer. $S_1^{L1\downarrow}$ can be seen as a "source" term of the diffuse intensity in (1).

The solution of the specific intensity I_L is discussed elsewhere [(4)]. When comparing the RT model with experimental data, the received power can be found from:

$$P_r = \int_{\Delta\Omega} T_{01} I_L(\theta, \phi, z=0) d\Omega \qquad (2)$$

where the integration is performed over the solid angle ΔΩ that subtends the area dA as illustrated in Fig.N1(b).

Figure N.2 shows a comparison between results available in the literature[6] and a simulation obtained at the NEAR-Lab for the solution of the transient RT equation.

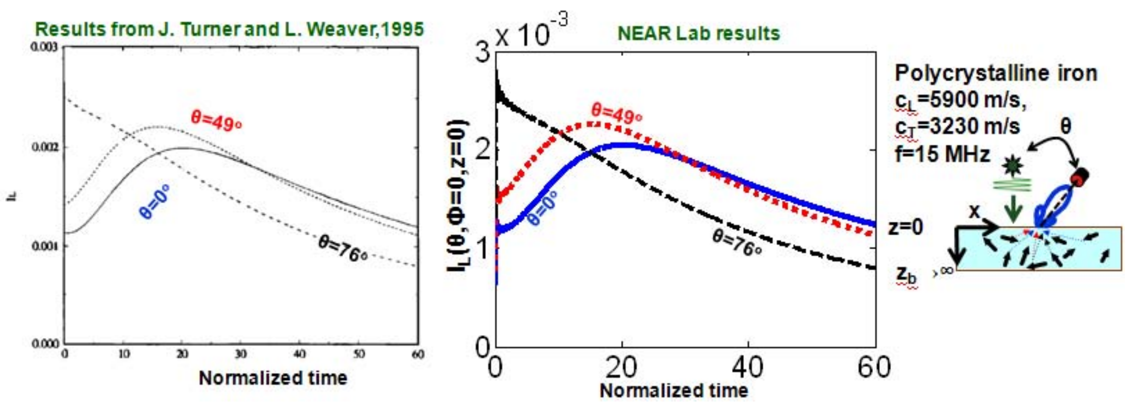

Figure N.2: Example of the solution of the Transient RT equation with polycrystalline iron as scattering media, and comparison with published results by Turner and Waver[6]. The simulation computes the diffuse intensity I_L from polycrystalline iron media when the excitation is a short impulse with f=15 MHz.

EXPERIMENTAL RESULTS

a- Scattering from glass beads embedded in resin (0.5<ka<0.9): a special material manufactured for scattering experiments was provided by Dr. Jean-Pierre Sessarego (Laboratoire de Mecanique et d'Acoustique,CNRS) to perform measurements of volume scattering. It consists of a slab of resin with

a 10% fractional volume of 1 mm diameter glass beads as scatterers. The elastic properties of the slab are taken from published results by Canepa et al[15]. These parameters are the input to the RT model to obtain simulated results for comparison. Figure N.3 shows the experimental setup, consisting of a broadband source (250 kHz->450 kHz), an omnidirectional receiver, a rotary stage and a supporting aluminum frame.

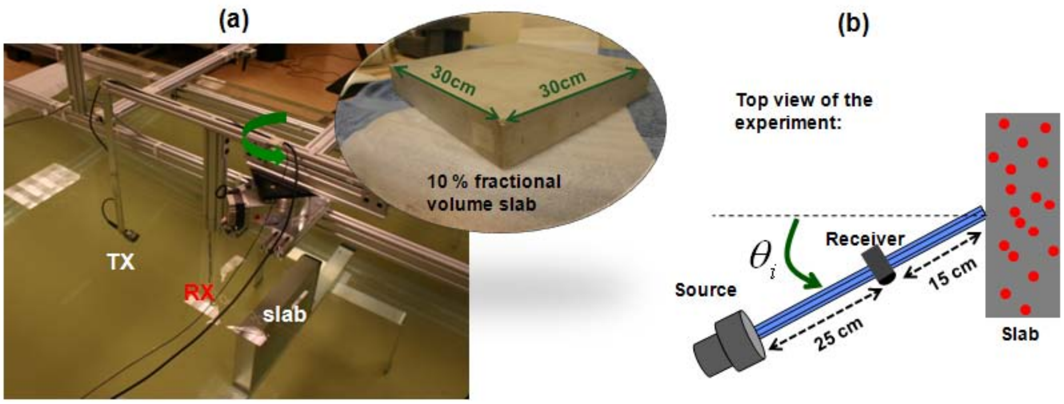

Figure N.3: (a) Picture of the experimental setup for measurements of angle-dependent volume scattering. The scattering media consists of a resin slab with 10% fractional volume of glass beads as scatterers; (b) Top view diagram of the measurement setup.

Measurements of backscattering were taken at incidence angles from θ_i= 0^o to θ_i=75^o. At each angle, 30 realizations were measured, were one realization consists on laterally shifting the position of the slab to obtain scattering from a different ensemble of glass beads. The measured scattering cross section $\Gamma_{av}(f,\theta_i)$ is shown in Fig. 4 (a), along with the computed values from the RT model. Figure 4 (b) shows similar measurements by Canepa et al[15] at 500 kHz using the same slab, where individual realizations are shown as dots and the solid line represents the average. Considering the large variability between realizations, the RT model predicts values close to the ensemble average.

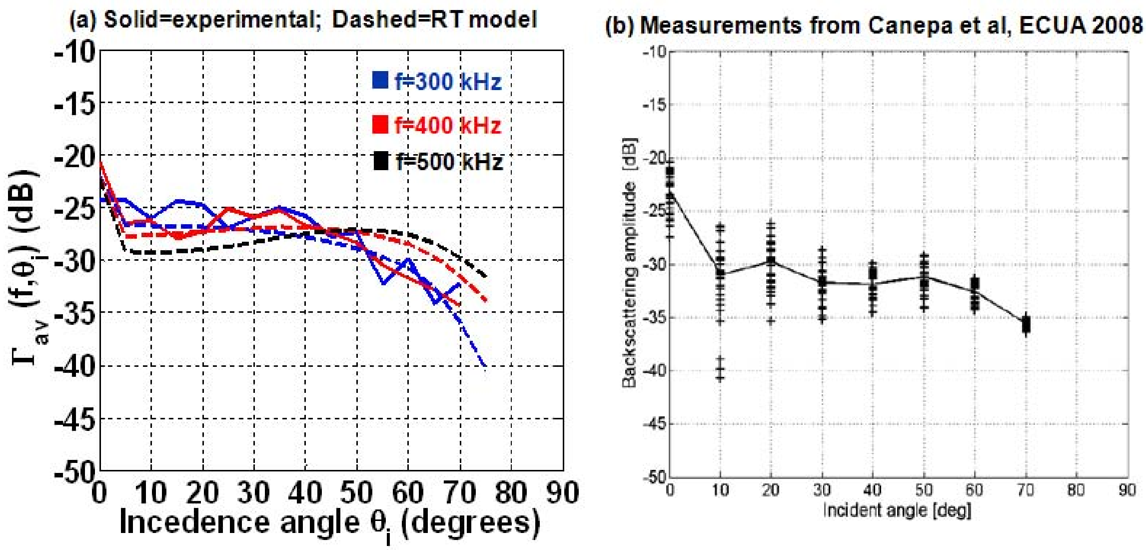

Figure N.4: (a) Measured scattering cross section at f=300 kHz and f=400 kHz as a function of angle of incidence, compared to the values computed using the RT model. A detailed description of the processing of experimental data can be found in Quijano et al[16]; (b) Results from Canepa et al[15] using the same slab, for comparison to the RT model at f=500 kHz.

b) Scattering from aluminum spheres in sand (5<ka<9): For this experiment only normal incidence measurements ($\theta_i = 0$) were considered. Aluminum spheres of radius a=4.8 mm where randomly distributed within a slab of fine sand (grain size between 200 and 400 μm). As a previous step to positioning the scatterers, the frequency-dependent attenuation of the sand was measured, since this is a required input parameter for the RT model. It was also found that the sand itself contributes to volume scattering probably due to trapped air bubbles, as shown in Fig.N5.

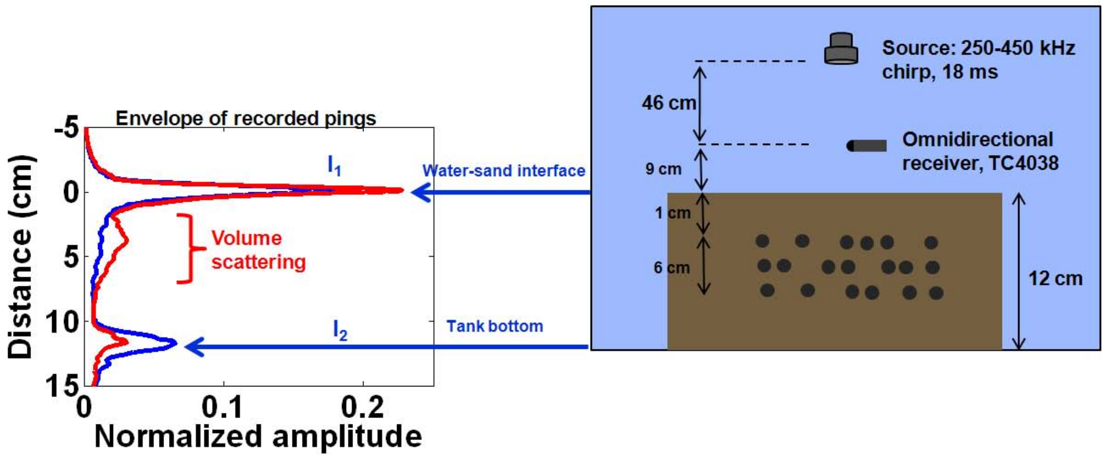

Figure N.5: Acoustic returns from the sand-water interface, the bottom of the tank, the background sand and the aluminum scatterers measured at normal incidence. The blue and red lines correspond to scattering from the sand with and without aluminum scatterers, respectively. Note that even in the absence of aluminum scatterers (blue curve), a small amount of volume scattering can be measured from the sand background.

As verification of the calibration of the system, scattering from a reference aluminum plate was measured. Figure N.6 shows that as expected, the scattering from this (almost) perfect reflector is flat and around 0 dB. Figure N.6 also shows the average over 70 realizations of the acoustic signal reflected from the sand-water interface, giving a bottom loss around -10 dB. The measured scattering cross section $\Gamma_{av}(f,\theta_i=0)$ due to the aluminum spheres is shown in the solid red curve. This cross section was obtained by taking an average over 70 realizations, and subtracting the average scattering from the sand itself (measured before placing the aluminum scatterers in the sand).

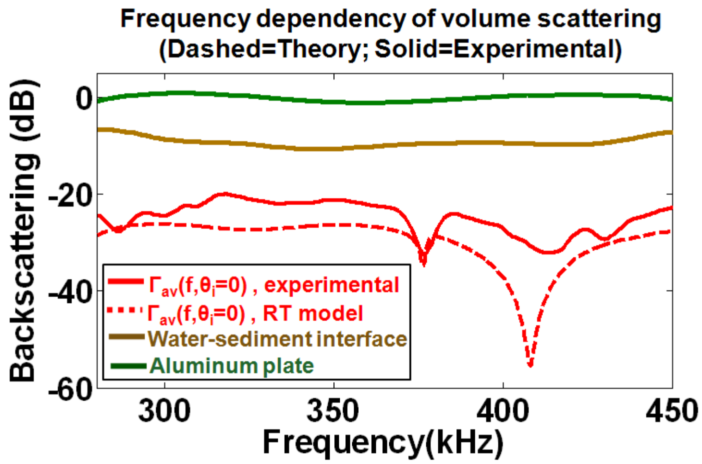

Figure N.6: Measured scattering cross section from aluminum spheres embedded in a sand slab, with a 5% fractional volume. The solid red line shows the experimental cross section, while the dashed line corresponds to the value obtained from the RT model. The reflected power from the sand-water interface is shown in brown, and as a reference, the reflected power from a (perfect) aluminum reflector is shown in green.

The scattering cross section predicted from the RT model is shown as a red dashed line, and it resembles the measured volume scattering except for a large resonance around 400 kHz that was not observed in the experimental data, and this is still subject of further investigation.

A more detailed description of these and other experimental results can be found in Quijano et al[16]. The experimental results have shown that the RT model can be used to predict backscattering in a variety of experimental conditions. The experiments performed at the NEAR-Lab have successfully validated the RT model by varying the frequency of operation, the size of the scatterers relative to the wavelength and the characteristics of the background material. Additional experimental work is required for the validation of the transient RT model to obtain time domain series of the scattering process.

While the current model is well suited for layers with discrete scatterers, an important extension is to include continuous (depth-dependent) variations in the sediment sound speed or density, so the RT model can also be compared to other classic formulations currently used. This extension has not been implemented yet for acoustics, but several publications in the area of electromagnetic remote sensing address the topic and can be translated to the elastic case.

IMPACT/APPLICATIONS

Many Navy sonar systems operate in the mid-frequency (1-10 kHz) band (for example, surface ship active ASW, SQS 53). In shallow water regions (depths of 100-200 m) the performance of these systems is strongly influenced by the presence of environmental variability. The impact of this work is

to provide an understanding of the spatial and temporal characteristics of the acoustic field in the mid-frequencies in order to optimize sonar performance.

RELATED PROJECTS

- Physics-Based Processing for Sonar Mapping of Coral Reefs; (FY07, sponsored by the Nature Conservancy).

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